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Preliminary Results of the Optical Observations of Three Microquasars

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Abstract About 15 microquasars have been discovered up to now. Since 1992, we have established a long-term program to monitor in optical and near-infrared bands the variability of 20 X-ray binaries, including several microquasars. The main goal of this program is to search for clues of the interaction between compact stars and their mass-donor stars, and to learn more about the multiwavelenth properties of X-ray binaries. We present the preliminary results of the observations of three microquasars in the optical band during our long-term program.

Key words: stars: binaries: general — X-ray: binaries — stars: microquasars

1 INTRODUCTION

Microquasars are X-ray binary systems that produce relativistic jets. They are stellar-mass black holes or neutron stars that mimic, on smaller scales, many of the phenomena seen in quasars. Microquasars are analogous to quasars not only from the morphological but also from the physical point of view. In addition, microquasars are considered to be good laboratories for understanding the physics of accretion and/or ejection processes and strong gravitational fields (see Mirabel & Rodríguez 1999 for a review). The key parameter that distinguishes the quasar and microquasar properties is believed to be the mass of the compact object in the central engine, varying over nine orders of magnitude from supermassive to stellar-mass black holes.

The number of sources of this type currently known in the Galaxy is about 15 (see Paredes 2004 and refer therein), among 50 radio emitting X-ray binaries within the 280 known X-ray binaries (Liu et al. 2000; 2001). More recently, Durouchoux et al. (priv. comm.) claimed that they had discovered 5 new microquasar candidates related to INTEGRAL sources. The number of microquasars could increase dramatically if radio emission from X-ray binaries always arises from relativistic jets, as it has been proposed by Fender & Hendry (2000). This would imply that all radio emitting X-ray binaries are microquasars.

Microquasars are found both in high-mass binaries and low-mass binaries, harboring either black holes or neutron stars. They show a rich phenomenology at different bands from radio, infrared, optical, X-ray, to γ-ray. In order to investigate the multiwavelenth properties of microquasars, we have established a long-term program to monitor a group of microquasars, in both optical and near infrared bands. Here we report the preliminary results of the optical observations of three microquasars.

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Table 1 Basic information of the three microquasars

Name	D (kpc)	V (mag.)	Sp. type	M_x ($M_\odot$)	P_{orb} (days)	β_{app}	Jet size (AU)
SS 433	4.8	14.2	A3-7 I?	11±5	13.1	0.26	$\sim 10^4 - 10^6$
LSI +61°303	2.0	10.7	B0 III-Ve	2±1	26.5	≥ 0.4	10 – 700
Cyg X-1	2.5	8.9	O9.7 Iab	10.1	5.6	—	~ 40

2 OBSERVATIONS

The program formally began in 1992 when the 2.16 m telescope was mounted at National Astronomical Observatories, China. A sample of 20 observable X-ray binaries were selected to monitor their long-term variabilities, including the three persistent microquasars, SS 433, LS I +61°303 and Cyg X-1. The optical spectroscopy with intermediate-resolution of 1.22 $\AA$/pixel was made with a CCD grating spectrograph at the Cassegrain focus of the telescope. Sometimes low-resolution spectra were also obtained. All spectroscopic data were reduced with the IRAF package. He-Ar spectra were taken in order to obtain the pixel-wavelength relations. They were bias subtracted and flat-field corrected. The basic information of the three microquasars is summarized in Table 1.

3 SS433

SS 433 is the first relativistic radio jet source detected in our Galaxy. Even after more than twenty years of study (Eikenberry 2001; Gies et al. 2002), SS 433 is still one of the most mysterious X-ray binaries. The compact star is likely a black hole, while the donor star is probably an A3-7 I star filling its Roche lobe (Hillwig et al. 2004). The system has an orbital period of 13 days, and the binary is likely embedded in an expanding thick disk that is fed by the wind from the super-Eddington accretion disk (Zwitter et al. 1991). The most interesting property of the binary is that both "stationary" and "moving" emission lines can be observed in its optical spectra. The radial velocity of the "moving" lines has a 162-day period which could be well explained by the "kinematic model" (Abell & Margon 1979). The moving emission lines are formed in the relativistic jets with a velocity $v = 0.26c$ and their features indicate that the ejecta from the binary is ballistic (Gies et al. 2002; Chakrabarti et al. 2002; 2003).

A journal of our observations is given in Table 2. Our spectra did not cover the right region of the stationary Hα emission line, due to the limited spectral coverage. We could only get the moving lines from the approaching jet (-Hα) and some pieces of receding one (+Hα). Figure 1a shows the spectral region from 5800 Å to 6700 Å where the moving lines are marked with -Hα (approaching) and +Hα (receding). We use the 5-parameter kinematic model (Eikenbery et al. 2001) to fit the Doppler shifts of the Hα moving lines. Our data fit the kinematic model well (Fig. 1b) and we could know that the Hα moving lines of our spectra in 2001 (open circles in Fig. 1b) are from the receding jets.

The stationary Hα and HeI emission lines of SS 433 have two different components. One is formed in the wind of the accretion disk and its intensity changes with the precessional phase. When the precessional phase is near zero (corresponding the largest projected area of the accretion disk in the sky) the emission intensity is the strongest and when the disk is edge-on the emission intensity reaches its minimum. Another component of the stationary emission lines is formed in the accretion flow from the donor star to the compact star when the disk is near edge-on and the donor star is close to its superior conjunction. At this time the donor star is below the accretion disk and we could see an accretion flow moving toward us. As a result we find a blue-shifted component in the left side of the HeI λ5876 and the Hα line in the 2001 spectra, but we could not find this blue-shifted component in other spectra.

Table 2 Journal of the Spectroscopic Observations of SS 433

Date	Julian Date (–2450000)	Orbital Phase(φ)	Precession Phase(Φ)	Hα EW (-Å)	Z1 (Receding)	Z2 (Approaching)
2001.09.30	2183.0975	0.4906	0.4710	376.0	0.0063	–
2001.10.01	2184.0689	0.5649	0.4770	411.7	0.0060	–
2002.10.22	2569.9641	0.0676	0.8569	267.8	–	–0.0778
2002.10.23	2570.9521	0.1431	0.8630	259.7	–	–0.0788
2002.10.26	2573.9777	0.3744	0.8816	310.8	–	–0.0946
2002.10.28	2575.9946	0.5286	0.8941	320.8	–	–0.0836
2003.10.14	2927.021	0.3655	0.0589	304.8	–	–0.0915
2003.10.15	2928.0372	0.4432	0.0652	468.0	–	–0.0874
2003.10.16	2928.9968	0.5166	0.0711	388.9	–	–0.0887

Note: the ephemeris of the orbital phase is from Crampton et al. (1980) and the ephemeris of the precession phase is from Gies et al. (2002).

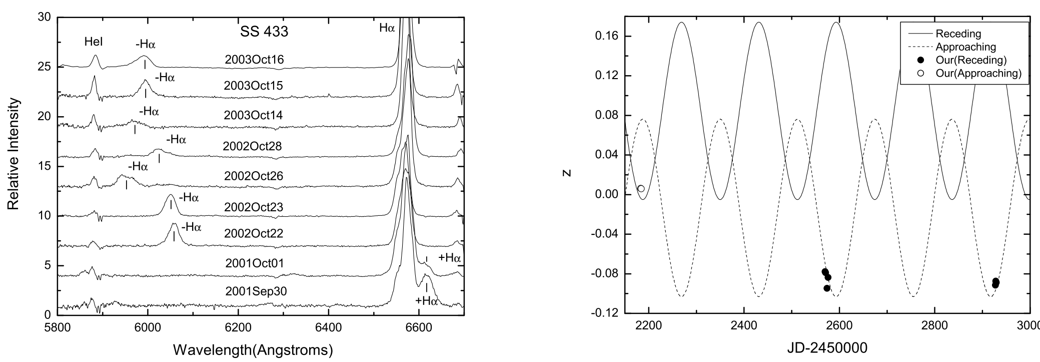

Fig. 1 **1a** (left panel): The spectra of SS 433 in 5800–6700Å. **1b** (right panel): Our data of SS 433 fit the simple kinematic model of Eikenbery et al. (2001).

4 CYG X-1

Cyg X-1 is one of the most extensively studied X-ray sources. Webster & Murdin (1972) and Bolton (1972) independently associated the X-ray source with the O9.7Iab supergiant HDE 226868, and found an orbital period of 5.6 days. Cyg X-1 is a detached double system but the optical component is very close to filling its Roche lobe. The masses of the two components were calculated as $17.5\,M_\odot$ for the supergiant and $10.1\,M_\odot$ for the black hole, with adopted system inclination (Herrero et al. 1995). The black hole was likely formed through direct collapse (Mirabel & Rodrigues 2003). Radio jets were recently discovered in Cyg X-1 (Stirling et al. 2001), indicating a collimated outflow with a speed in excess of $0.6c$, so Cyg X-1 joined the group of Galactic microquasars (Mirabel & Rodríguez 1999). Previous optical study of the emission spectrum of Cyg X-1 showed that the Hα line-profile has strong variability on the orbital period (Gies & Bolton 1986; Sowers et al. 1998), as well as high phase-independent variability (Tarasov et al. 2003).

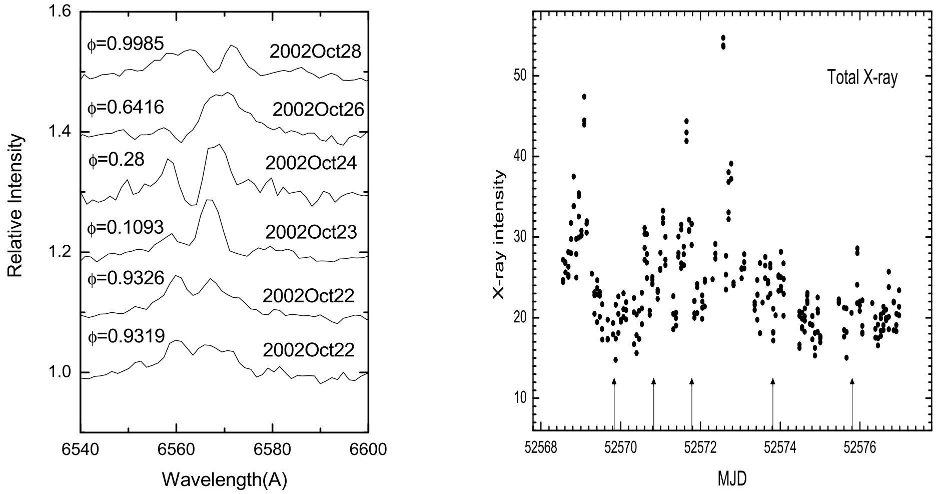

Fig. 2 **2a** (left panel): Variability of the Hα line of Cyg X-1 during our program, covered a whole orbital period. The ephemeris was from the recent estimation based on spectroscopic and photometric orbital variability (Brocksopp et al. 1999). **2b** (right panel): RXTE ASM observations in 1.5–12 keV band. The optical observation epochs are indicated.

We have taken the spectroscopy of Cyg X-1 since 2001. The Hα line is highly variable. In Fig. 2a we show the Hα lines of Cyg X-1 in 2002, which covered a whole orbital period. All spectra were taken just after the X-ray high/soft state of 2001 September. The simultaneous RXTE ASM X-ray data are plotted in Fig. 2b, with the optical observation epochs indicated. Both orbit-independent and orbit-dependent variabilities of the spectra of the Hα emission line are apparent. The Hα profile appears to have at least two components; P Cygni emission moving with the orbital motion of the primary star and a second emission component which is formed in the focused wind flow between the stars.

5 LS I +61°303

LSI +61°303 is a Be/X-ray binary system associated with the galactic plane variable radio source GT0236+610 (Gregory & Taylor 1978). The system was probably ejected from the nearby cluster IC 1805 in an asymmetrical supernova explosion (Mirabel, Rodrigues, & Liu 2004). Extensive radio observations yielded a periodic variation with a period of 26.5-day (Taylor & Gregory 1982). The radio period was confirmed by Hutchings & Crampton (1981) with analysis of three-year observations of radial velocity. Periods close to the orbital 26.5 day radio period have also been detected in the optical (Mendelson & Mazeh 1989), in the near infrared (Paredes et al. 1994), in the X-rays (Paredes et al. 1997), and in the γ-rays (Massi 2004). There have been various studies of the optical continuum emission and the variability of its emission lines as well as the infrared excess characteristic of the Be star. The variable radio counterpart of LS I +61°303 (Gregory et al. 1979) has been resolved at milliarcsecond scales as a rapidly precessing relativistic compact jet (Massi et al. 2001; 2004).

Fig. 3 shows the long-term variability of the Hα emission line of LS I +61°303. The normalized Hα records of LS I +61°303 are ordered sequentially with observing time and drawn on the same scale with same offset. Although the Hα emission line is highly variable, the Hα line profile has not changed its main feature for more than a decade. Another obvious phenomenon is that

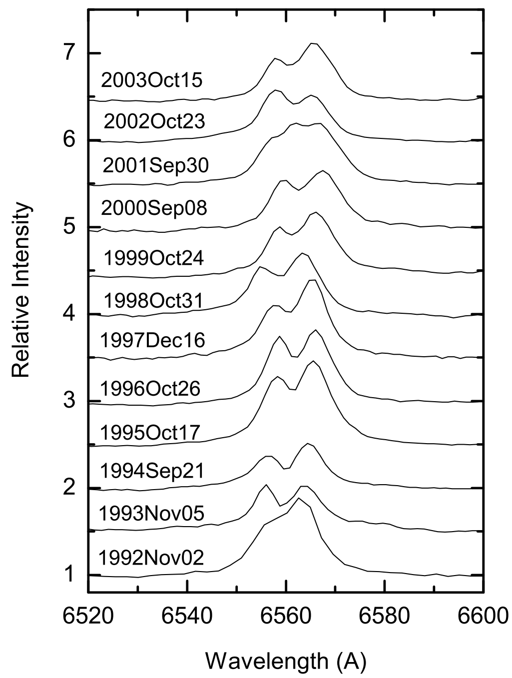

Fig. 3 Selected Hα spectra of LS I +61°303 taken during our long-term program.

the intensity of the red peak of the double Hα emission line is always larger than that of the blue one, except for the spectrum on 23 Oct. 2002 at orbital phase 0.39, in which the intensity of the red peak is slightly weaker. We suggest that the pattern of the Hα emission line is likely to be caused by the periodic accretion of the neutron star. The neutron star begins to accrete stellar material when it approaches the periastron, resulting in the additional loss of stellar material due to the high eccentricity. The inclusion of the neutron star results in significant departures from a simple, spherically symmetric wind. Stevens (1988) found in another highly eccentric Be/x-ray binary, A0538-66, that the mass-loss rate of the primary in the direction toward the neutron star can be enhanced by a factor of up to 200, when the neutron star is close to the periastron. Therefore, the circumstellar disc structure in LS I +61°303 must differ from other Be stars, which results in the particular pattern of the Hα emission line.

6 CONCLUSIONS

We have monitored the spectral variability of three microquasars in the optical. The most interesting property of SS 433 is that we can find the "stationary" and the "moving" emission lines in its optical spectra. Both the receding and the approaching component of the Hα line in SS 433 are observed. The stationary Hα and HeI emission lines of SS 433 have two different components; one component of the stationary emission lines is formed in the accretion disk and another is formed in the accretion flow from the donor star to the compact star. In the spectra of the Hα line of Cyg X-1, we detect both orbit-independent and orbit-dependent variability. We show that the Hα profile of Cyg X-1 appears to have at least two components; P Cygni emission moving with the orbital motion of the primary star and a second emission component which is formed in the focused wind flow between the stars.

The Hα emission line of LS I +61°303 is highly variable. We find that the intensity of the red peak of the double Hα emission line is always larger than that of the blue one, except for the spectrum on 23 Oct. 2002. We suggest that the pattern of the Hα emission line is likely to be caused by the periodic accretion of the neutron star due to the high eccentricity, which results in significant departure from the case of a simple, spherically symmetric wind.

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